Unravelling the Magnetization of CORC, TWST, and Roebel Cables for HEP applications and Associated Error fields

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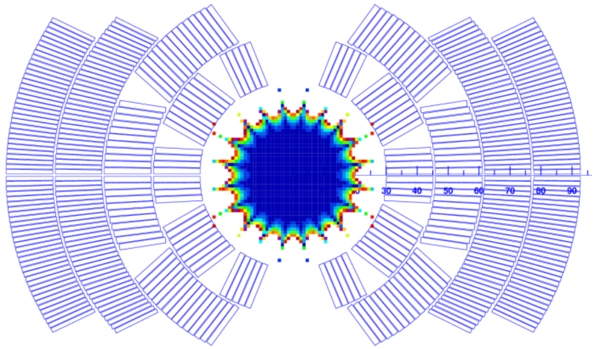
CSMM Center for Superconducting and Magnetic Materials

Department of Materials Science and Engineering

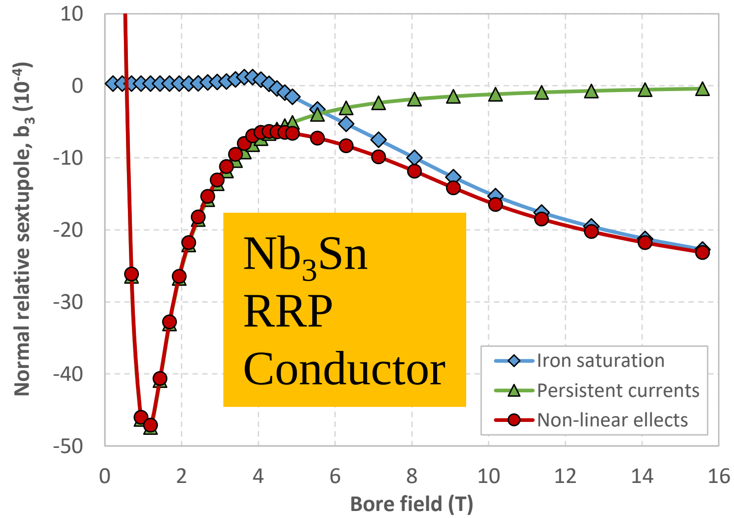
Outline of talk

- Motivation – accelerator quality
- Analysis of CORC and Twist Stack Cable Magnetization
- Results from 12 T cryogen free system
- Results from 3 T Dipole System
- Drift Suppression
- Comparison of Data and Theory

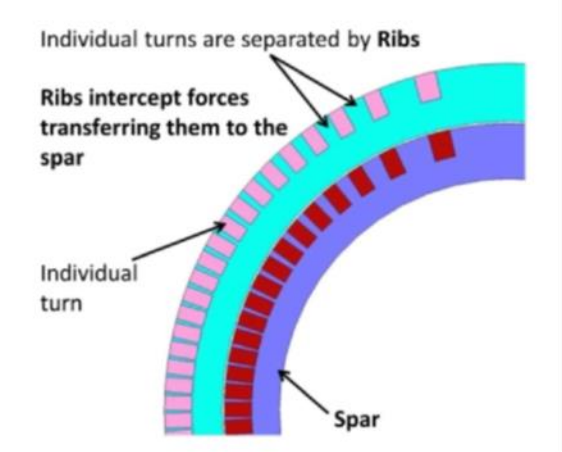
Motivation--Field Error in Accelerator Magnets



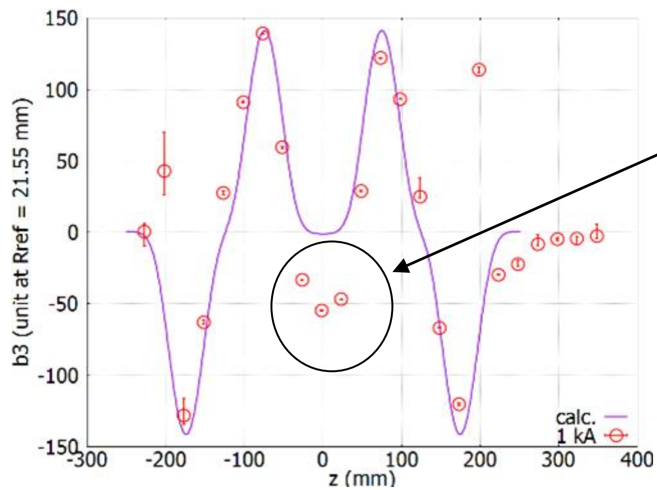
Cos theta



A Zlobin, “15 T dipole design concept, magnetic design and quench protection”, Presentation at the US MDP workshop Jan 2017



YBCO CORC Canted cos coil (Wang, LBNL 2018 MDP)

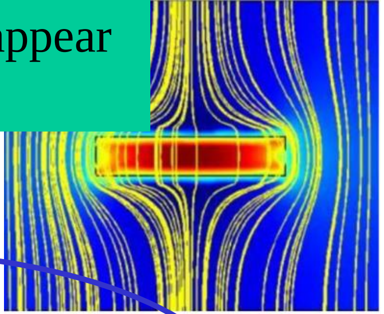


Magnetization related b3

Department of Materials Science and Engineering

What does the magnetization of HTS, esp YBCO, look like?

Summary of Loss expressions will appear in next edition handbook



$$Q = 2N\mu_0 H_0 J_c a$$

$$N = \left(\frac{H_0}{H_d}\right) g\left\{\frac{H_0}{H_d}\right\}$$

$$g\left\{\frac{H_0}{H_d}\right\} = \frac{H_d}{H_0}\left[\frac{2H_d}{H_0}\ln\left(\cosh\left(\frac{H_0}{H_d}\right)\right) - \tanh\left(\frac{H_0}{H_d}\right)\right]$$

For flat strands with B ⊥ tape

1. For B perpendicular, $B >> B_p$

$$\Delta M = aJ_c$$

a is half width

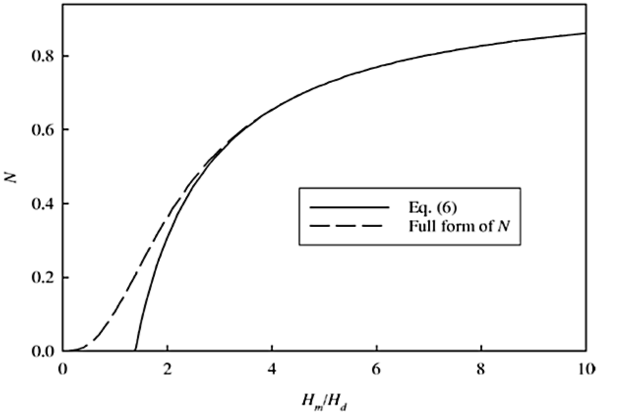
slabs

2. For B perpendicular, $B << B_p$

$$M = -\infty$$

As the width becomes infinite

3. For B perpendicular, $B \approx B_p$



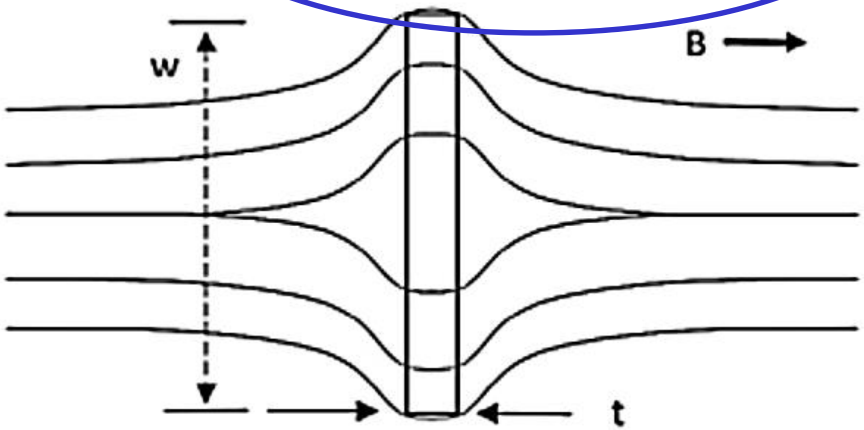


Figure 3. Field penetration into a thin slab (coated conductor).

The penetration field in this case is given by

$$H_p = \frac{J_c t}{\pi}\left[Ln\left(\frac{w}{t}+1\right)\right] = \frac{5}{2\pi}H_d\left[Ln\left(\frac{w}{t}+1\right)\right]$$

where $H_d = 0.4\,J_c t$ is a characteristic field. We note from Ref [16], that for $H_0/H_d > 3$

$$N \approx 1 - 2\left(\frac{H_d}{H_0}\right)Ln(2)$$

What does the magnetization of HTS, esp YBCO, look like - injection region?

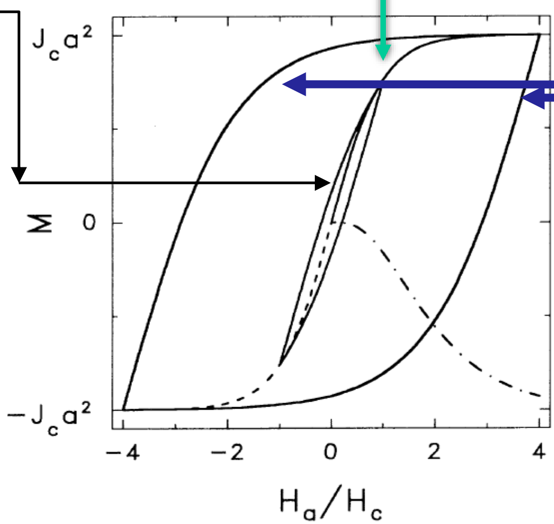
4. For B perpendicular, if we want M=f(H)

$$M_{\downarrow\uparrow} = \pm J_c a^2 \left[\tanh \frac{H_0}{H_c} + 2\tanh \frac{H_a \mp H_0}{2H_c}\right]$$

$$M = \pi a^2 H_a (1 - H_a^2/3H_c^2)$$

$H_a << H_c$

$$M = J_c a^2 [1 - 2\exp(-2H_a/H_c)] \qquad H_a \gg H_c$$



$M_{\uparrow\downarrow}$=M/L=$J_c ta^2$=$J_{cs}a^2$

a is half width of tape
H_a is applied field
H_c = J_c/π, where *J* is sheet current A/m
J_{cs} = usual J_c*t
H_0 = H_{max}
$M_{\uparrow\downarrow}$ is moment per unit length

M=m/Lta

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Type-II-superconductor strip with current in a perpendicular magnetic field

Ernst Helmut Brandt and Mikhail Indenbom*

CSMM Center fo

But What about Cables?

- A lot more Difficult for CORC and Twist stack!

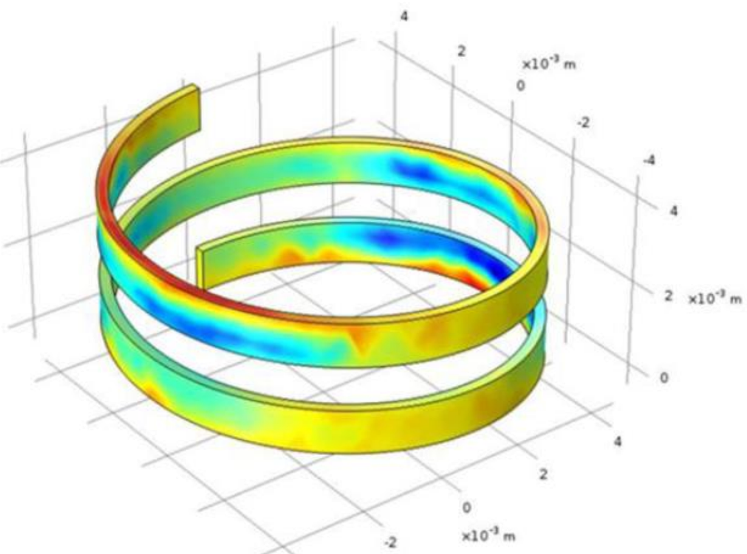
(helical, super high aspect ratio, node-hogging, multiple tape, tape-tape interaction, several loss components)

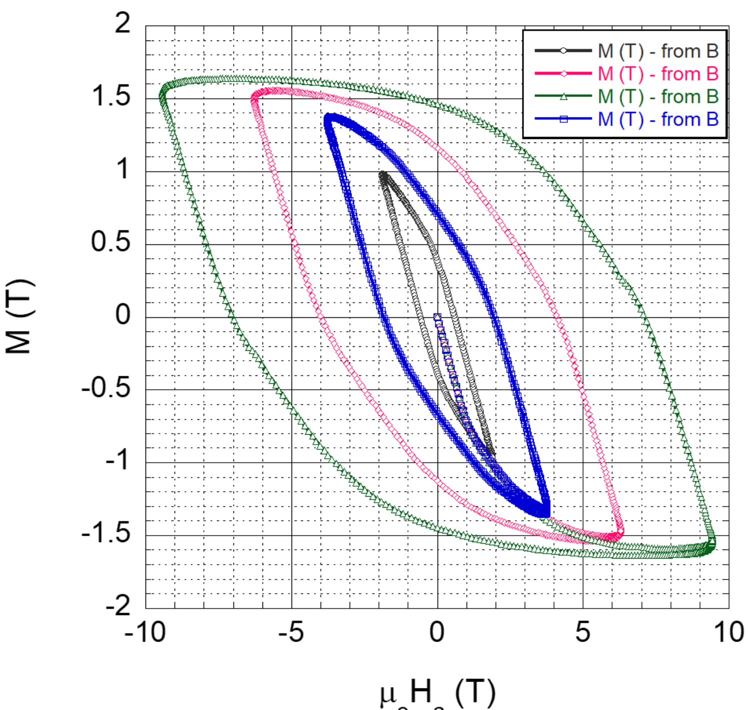
- Even Roebel has its complications!
- **<u>But, let us begin</u>**

Unravelling the CORC (and Twist Stack) Cable I

- Magnetization for coated conductor tapes is known
- A direct, analytic calculation for the loss of a CORC cable or a twist stack had not been performed, except at at $L_p \to \infty$, where
- $M_{hel} = \frac{2}{\pi} M_{tape}$ for an individual tape in a CORC or twist stack cable
- For all samples not in this limit (most samples), the magnetization is lower, but not known.
- The helical or twist geometry is a problem, as are the multiple layers of tape
- FEM approaches to the full problem are also not yet demonstrated because of large computational effort
- Desired is a simple expression to give the magnetization of CORC and twist stack cables
- Below we tackle this problem by first ignoring coupling and eddy currents, these can be added later
- We also simplify the problem to one tape in a helical or twisted geometry
- The individual tape response can be summed to give the cable response well above penetration field
- Magnetization at low fields (e.g. penetration fields) can be calculated later by computing the interactions among these layers
- Coupling current can be added back in later

Consider one tape of a CORC conductor – a helical wrap





This computation can be performed, but is quite demanding in terms of computation time

w_hel	**1 mm**	**Tape width**
th_hel	w_hel/4 = 0.25 mm	Tape thickness
r_hel	4.5 mm	Radius of helix axis
l_hel	(N_turns + 1)*w_hel + N_turns*gap = 5 mm	helix height
gap	w_hel = 1 mm	Gap between helix turns
pitch	w_hel + gap = 2 mm	Helix twist pitch
N_turns	2	Number of turns in helix
l_tape	N_turns*sqrt(pitch^2+(2*pi*r_hel)^2)=56.6899 623 mm	Tape length in helix
V_tape	w_hel*th_hel*l_tape =14.17249058 mm^3	Tape volume in helix
J_c	10^{10} A/m^2	Critical current density

$$\Delta M_{tape} = J_c a = 10^{10}\left(\frac{0.001}{2}\right) = \frac{5x10^6 A}{m}$$

$$= 6.25\ T$$

5000 kA/m

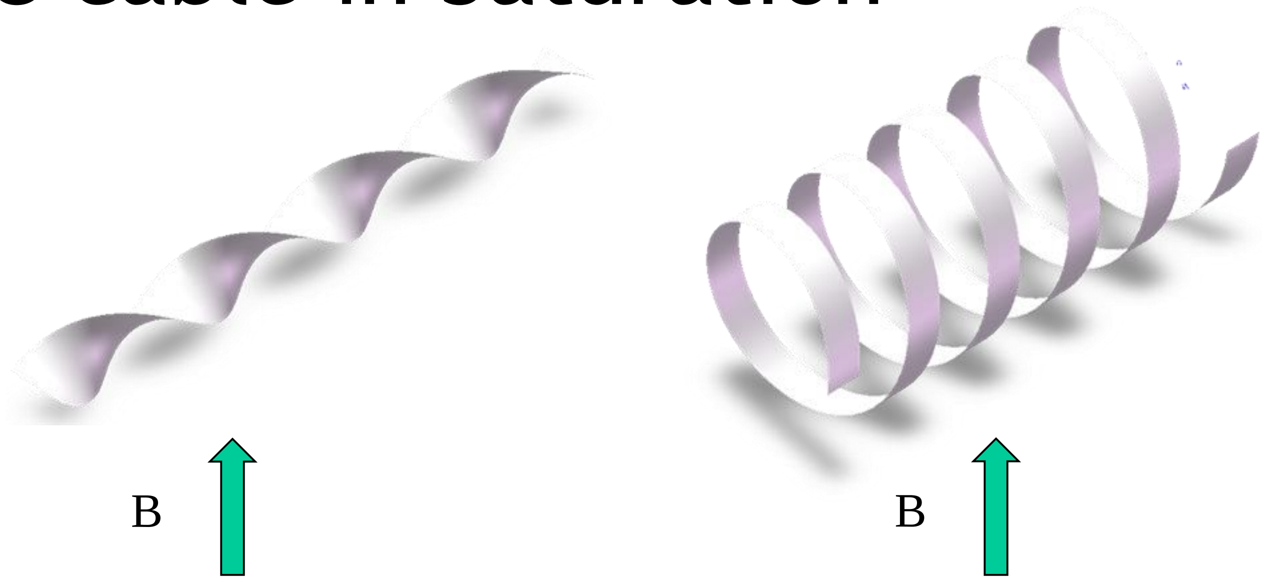
$$M_{helix} = \frac{2}{\pi} M_0 \frac{1}{2} = 1.59\ x\ 10^6\,\frac{A}{m} = 2\ T$$

Magnetization of a helical Tape or CORC cable in Saturation

In general, in full penetration,

$$Q_0 = 2\mu_0 H_0 J_c w$$

(here w is the half width)



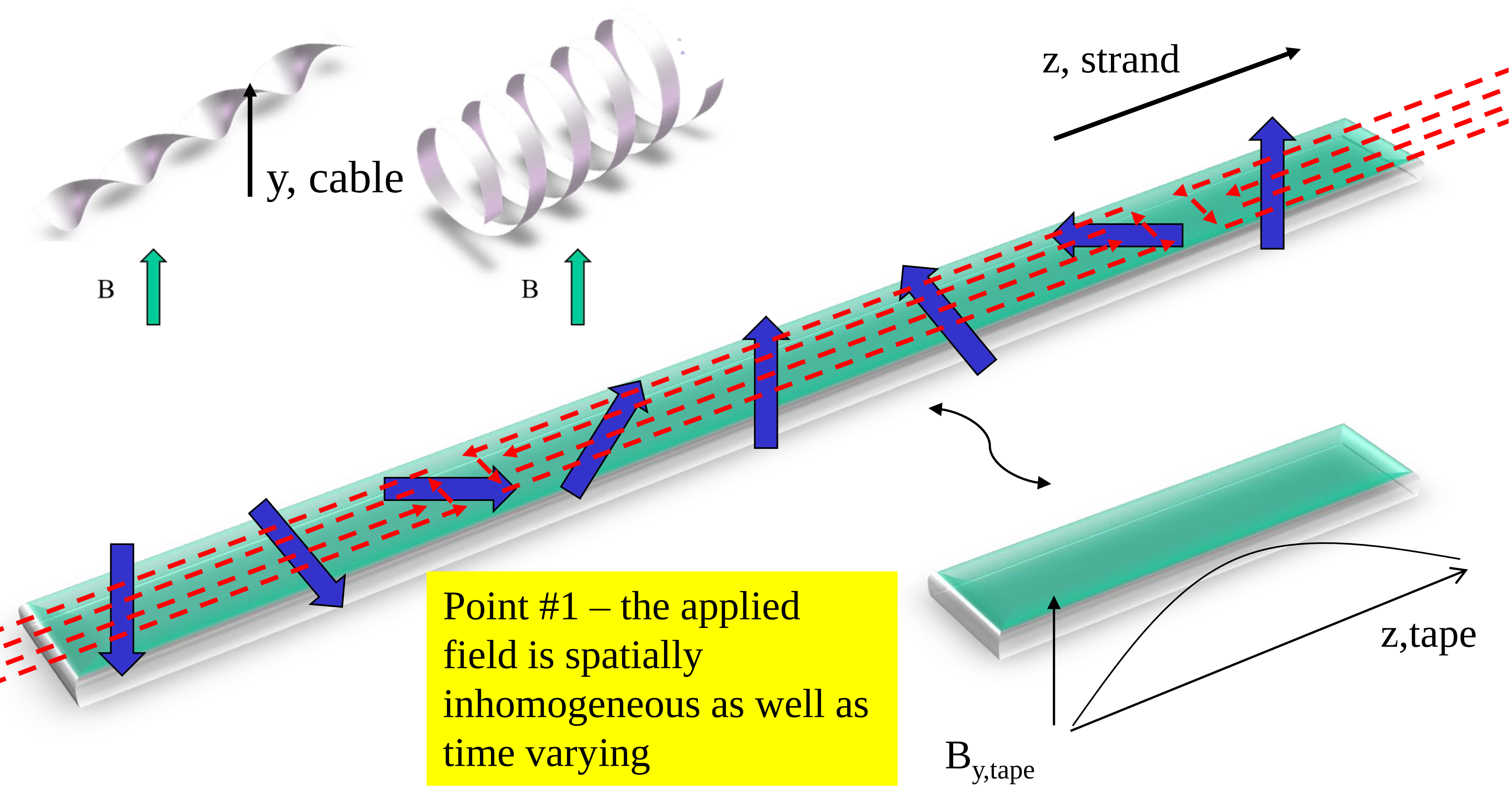
We might then imagine that that loss could be calculated by the simple expedient of integrating the average of Eq (5) over a spatial field cycle, such that

$$Q = \frac{2\mu_0 J_c w H_0}{L_p/2}\int_0^{\pi} sin\left(\frac{2\pi z}{L_p}\right)dz = \frac{2\mu_0 J_c w H_0}{L_p/2}\frac{L_p}{2\pi}(2) = \left(\frac{2}{\pi}\right)2\mu_0 J_c w H_0 = \boldsymbol{\left(\frac{2}{\pi}\right)Q_0}$$

This leads to $M = (2/\pi)M_0$. **Is this true?** Yes if $L_p >> w$, but in general, not……

Carr, AC Loss and Macroscopic Theory of SC, p 189, 2nd Ed

Let us consider the general case -- Magnetization of a helical Tape or CORC cable in Saturation II

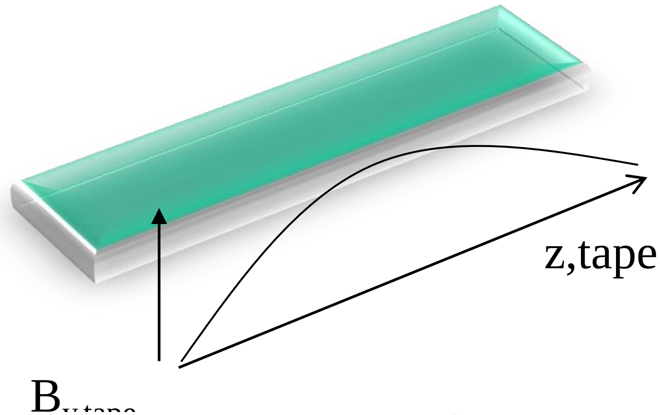


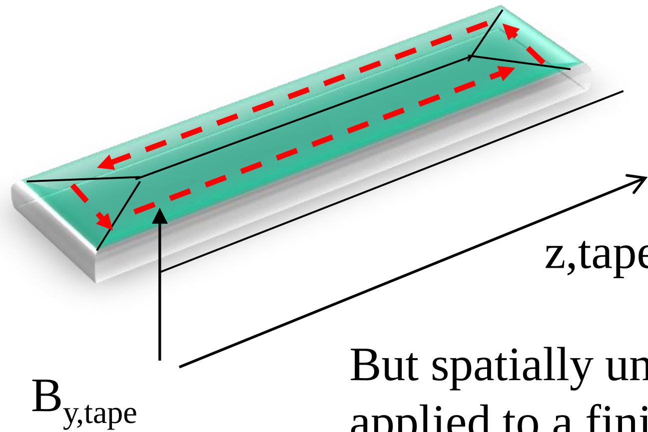
Point #1 – the applied field is spatially inhomogeneous as well as time varying

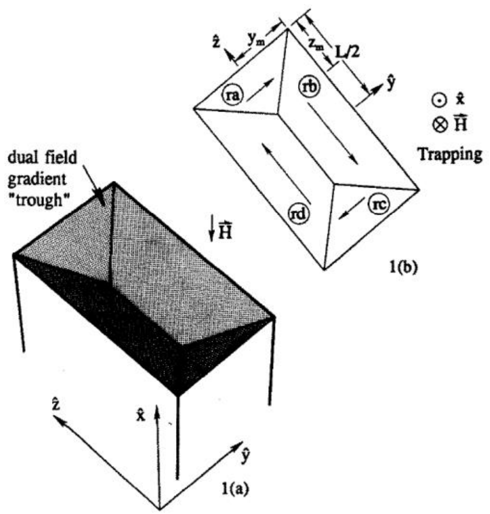
Magnetization of a helical Tape or CORC cable in Saturation III

2. In general, currents in the presence of spatially inhomogeneous fields not a solved problem

3. The current flow is also spatially varying, leads to "end effects!"







But spatially uniform field applied to a finite length sample is a solved problem

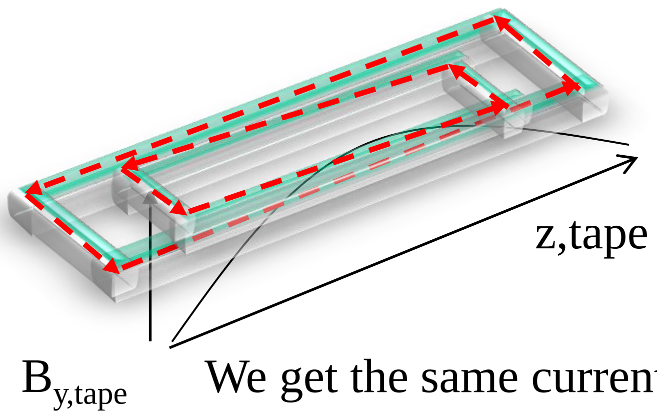
2. E. M. Gyorgy, R. B. vanDover, K. A. Jackson *et al.*, *Appl. Phys. Lett* **55**, 283 (1989).
3. F. M. Sauerzopf, H. P. Wiesinger and H. W. Weber, *Cryogenics* **30**, 650 (1990).
4. S. Hu, H. Hojaji, A. Barkatt *et al.*, *Phys. Rev. B.* **43**, 2878 (1991).

$$\Delta M = J_c y_m \left(1 - \frac{2y_m}{3L}\right) \qquad L/2 > Z_m$$

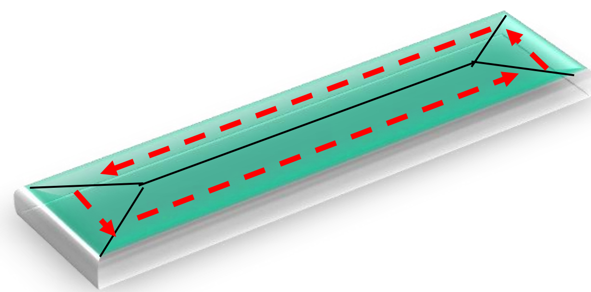
$$\Delta M = J_c \frac{L}{2} \left(1 - \frac{2y_m}{3L}\right) \qquad L/2 < Z_m$$

Magnetization of a helical Tape or CORC cable in Saturation IV

If we consider the field penetration layer by layer in a concentric shell configuration



We get the same current paths as the short sample in uniform field



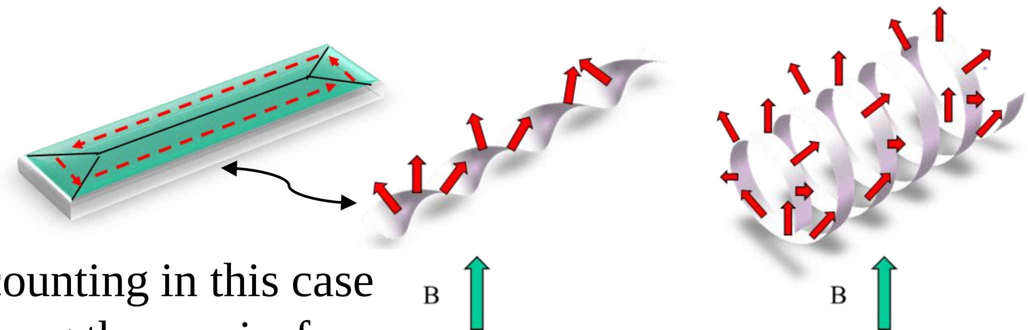
If $B >> B_p$,
in this case, B (at $L_p/2$-w/2) > $J_c w/2$

The local magnetization is changed, since M = <B>/μ0-<H> and <H> is lower
(M is reduced)

But, much more relevant for transforming back to the external field coordinates, the moment is the same as that of the finite sample in homogenous field (the demag leads to a lower local M)

Magnetization of a helical Tape or CORC cable in Saturation V

We can then use the moment of the short finite length calculation, breaking the twist or helix into a series of short samples



Integrating around the helix and accounting in this case for the component of the moment along the z-axis, for a twisted tape we get

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2y_m}{3L}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{w}{3\frac{L_p}{2}}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2w}{3L_p}\right)$$

Analytic Result!

For the helix it will be the same, but with L_{eff} in place of L_p

$$L_{peff} = \sqrt{L_h^2 + (\pi D_h)^2}$$

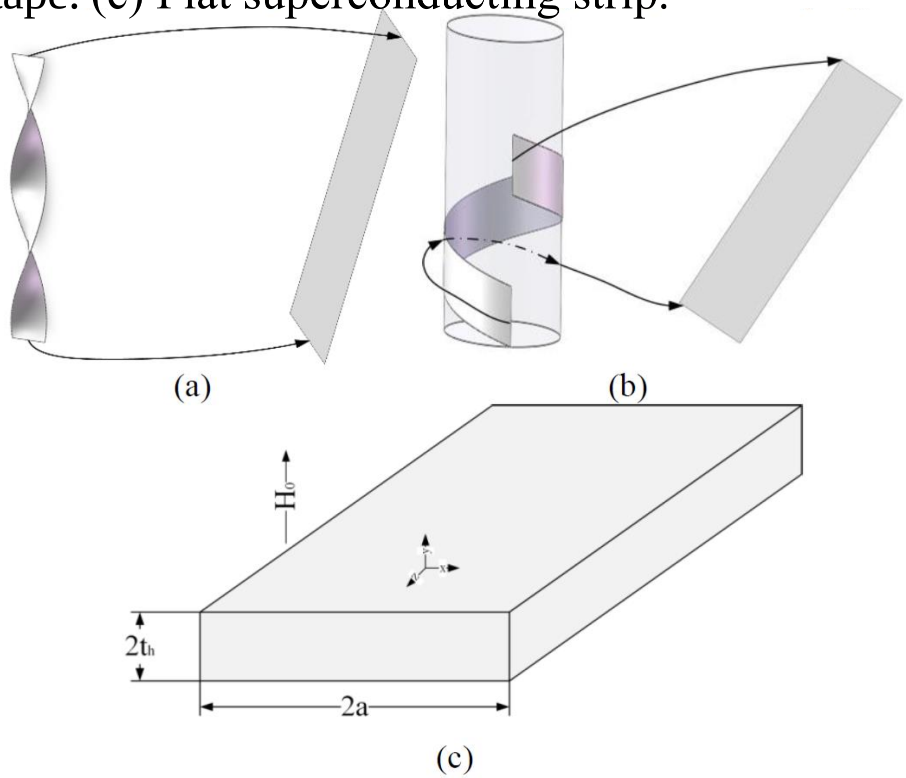
Twisted Tape: If $L_p > 20/3$ w (2.7 cm for 4 mm wide tape), $\Delta M_{twisted} \approx (2/\pi)\Delta M_{tape}$ with err < 10%

Helical/CORC Tape: **<u>Example 1:</u>** CORC Cable with L_h = 34 mm, OD = 4.76 mm, and L_{peff} =37 mm gives $\Delta M_{helical} \approx 0.85(2/\pi)\Delta M_{tape}$

<u>Example 2:</u> CORC wire with $L_h \approx 10$ mm, OD = 3 mm, L_{peff} = 13.7 mm, $\Delta M_{helical} \approx 0.80(2/\pi)\Delta M_{tape}$

Parallel FEM Approach – Again Unravelling the CORC (and Twist Stack) Cable

We consider first one tape from a CORC or a twist stack cable
Untwist the twisted superconducting cable into the mathematical model flat superconducting tape. (b) Unwind a single CORC tape into the flat superconducting tape. (c) Flat superconducting strip.

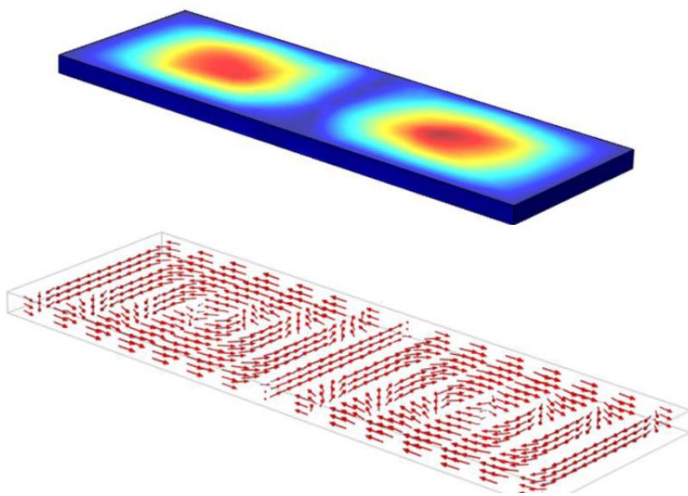


For a simple twisted Conductor, the twist pitch is straightforward, while for the helical wrap,

$$L_{peff} = \sqrt{L_h^2 + \left(\pi D_h\right)^2}$$

We then use Finite Element methods to calculate the Magnetization of a slab in a spatially inhomogeneous and time changing field

$$M = \left(\frac{1}{V} \int_V H_{local}\, dV - H_{applied} \right)$$



For a spatially uniform field

$$H_{applied} = H_{max} \sin(\omega t)$$

For a spatially varying field

$$\boldsymbol{H_{applied}} = \boldsymbol{H_{max}} \, \mathbf{sin}(\boldsymbol{\omega t}) \, \mathbf{sin}\left(\frac{\mathbf{2\pi z}}{\mathbf{L_p}}\right)$$

- The expressions for M are the same,
- Only the applied field is different.
- Since M=B/μ-H, the magnetization is the same except at very low fields

Simulations I

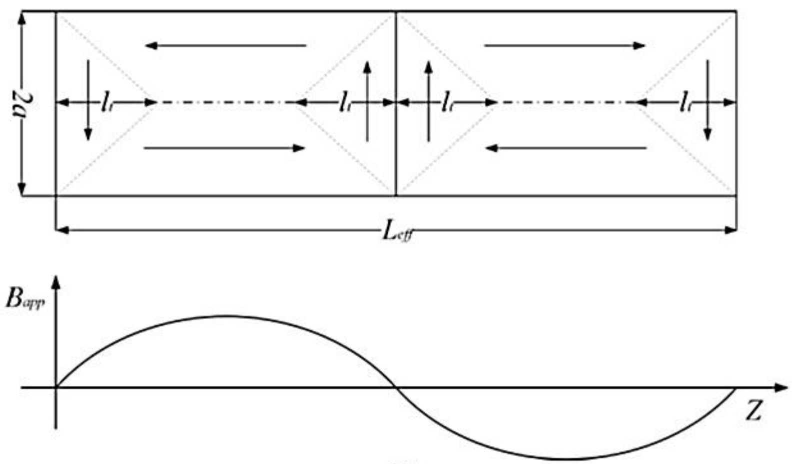
Normal Magnetic Field

Electric Field

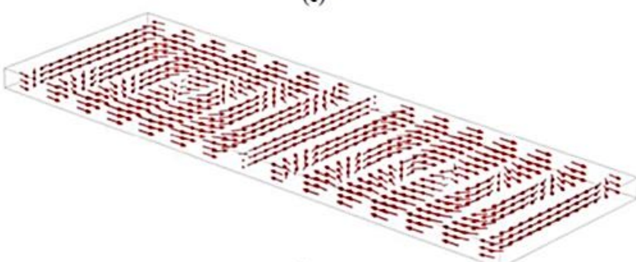
Simulations II –Electric field

Supercurrent Density

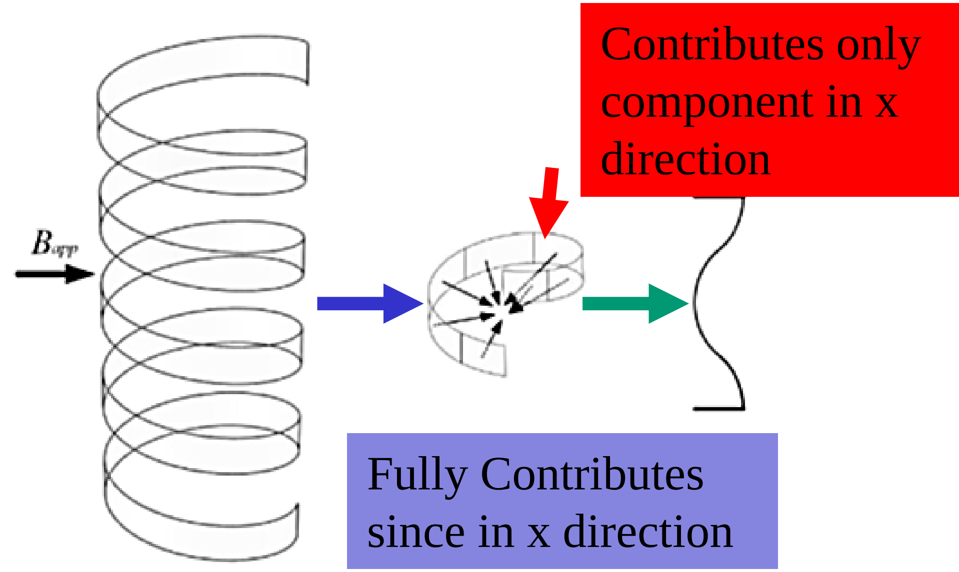
Then magnetic moments are re-assembled to generate the magnetization



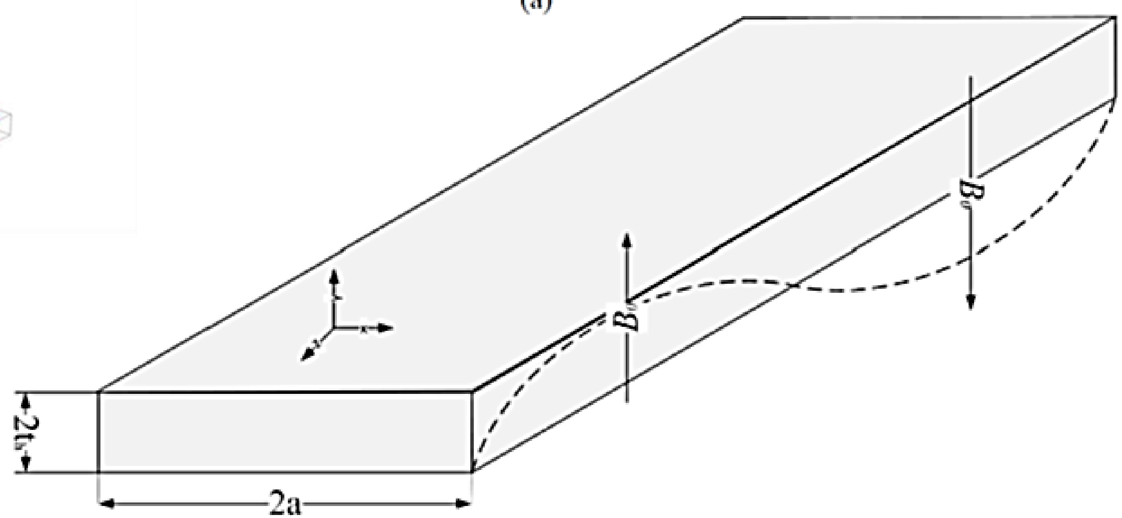
(c)



(d)



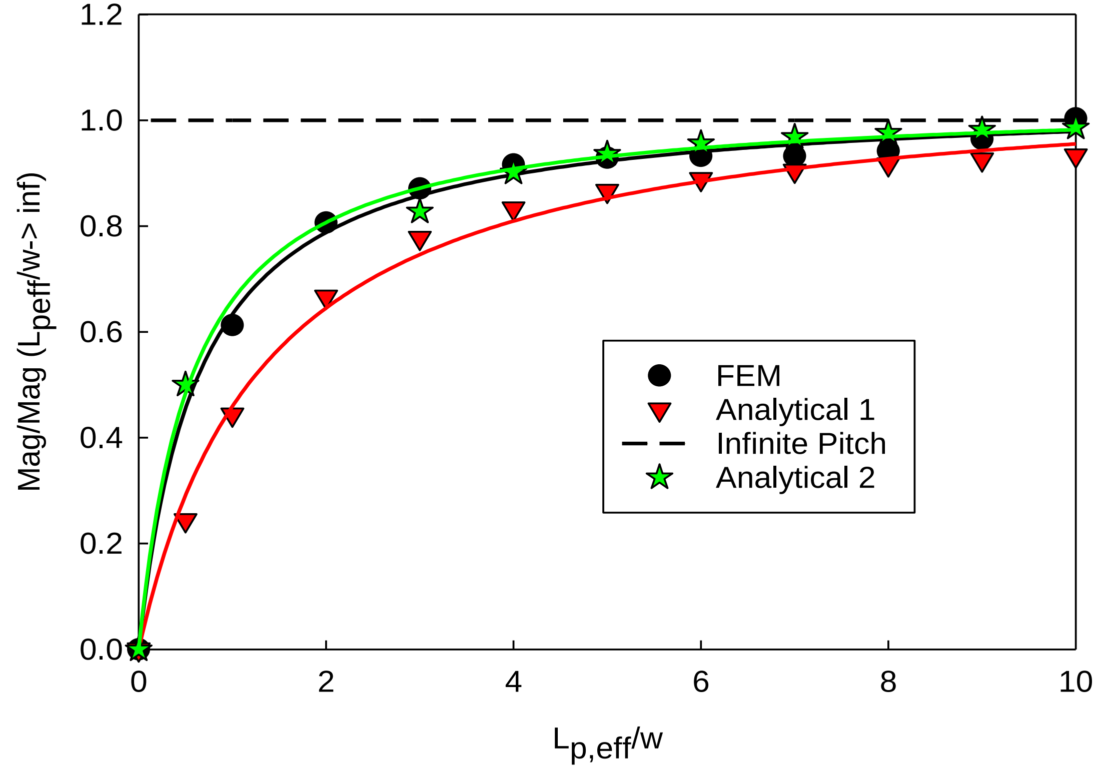
(a)



(b)

Comparison of FEM and analytic results

- Dashed line gives infinite pitch
- Shorter L_{peff}/w ratios give lower mag
- Agreement between FEM and analytic OK with Analytic 1
- Agreement even better when WF included – Analytic 2



Analytic 1

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2y_m}{3L}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{w}{3\frac{L_p}{2}}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2w}{3L_p}\right)$$

Analytic 2

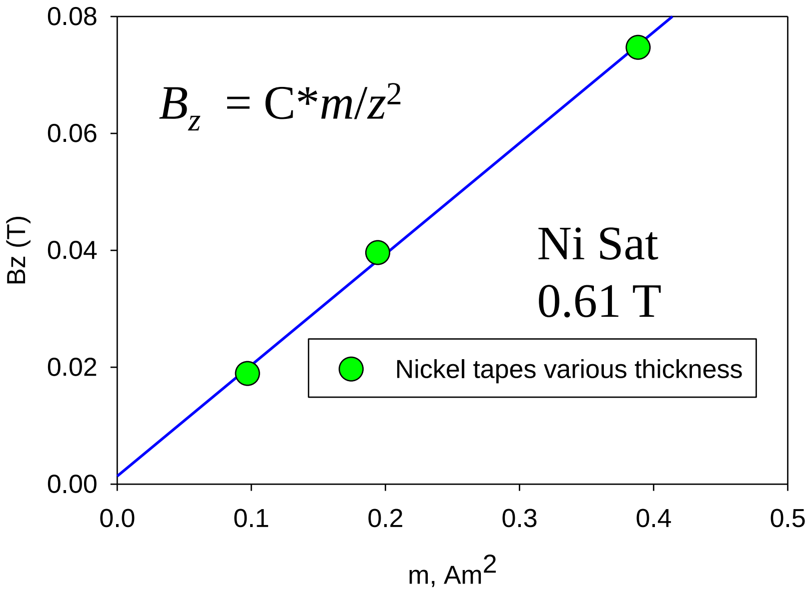
$$\Delta \mathrm{M} = \Delta M_0 \frac{L_p}{\pi w} \cos\left[\frac{\pi L_p}{4}\left(1 - \frac{w}{L_p}\right)\right]$$

$$WF = \frac{L_p}{\pi w} \cos\left[\frac{\pi L_p}{4}\left(1 - \frac{w}{L_p}\right)\right]$$

Measurements

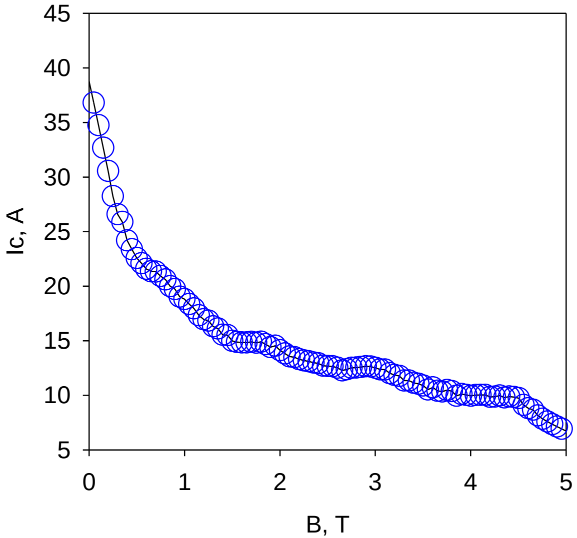
- 12 T 5 cm length hall probe system, hysteretic
- Cable measurement facility (±3 T, 60 Mhz)
- Drift Measurements, and Drift Compensation
- Data/Theory Comparison

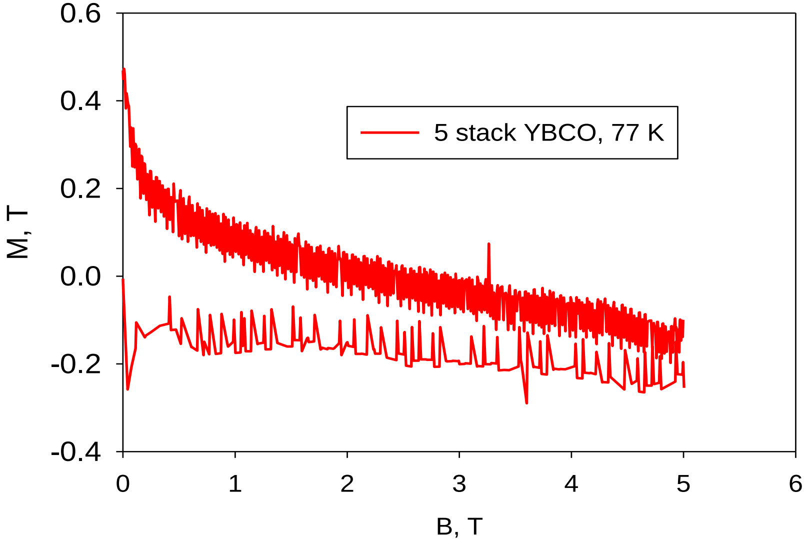
Hall Probe Magnetization in 12 T dry magnet with tail dewar – for tapes, short cables



Made for 12 T magnetization of tapes and short cables

- Sample up to 6 cm long
- Penetration field Determination
- Drift





Measurements with short hall probe system

Present Measurements

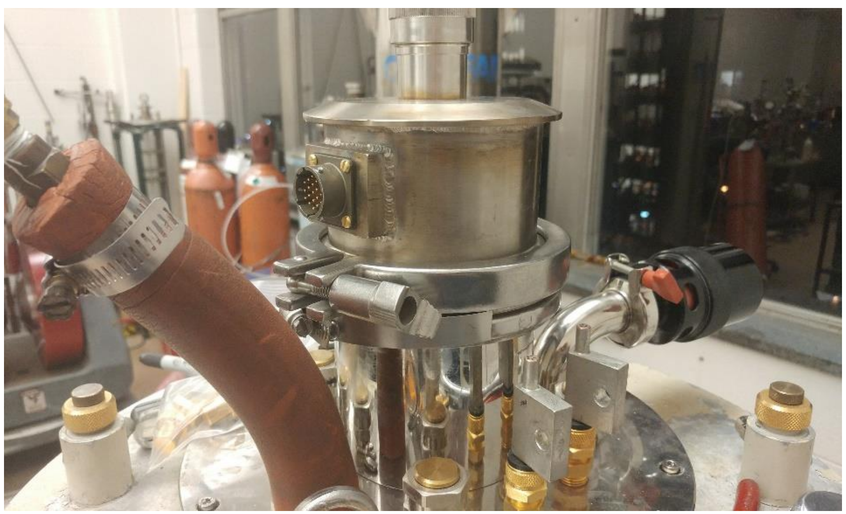
- Decay in twist stack
- Penetration field and injection magnetization measurements at 4.2 K for twist stack

Next

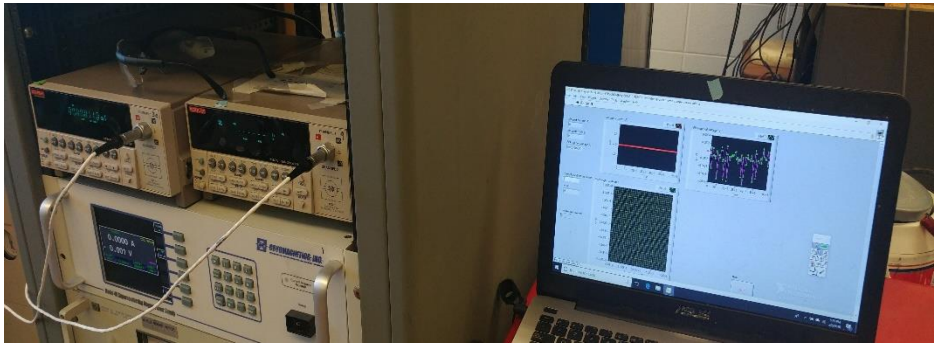
- Penetration field, injection magnetization, and drift, CORC and Roebel
- Good system to measure Bi-2212 wires with no helical wrap

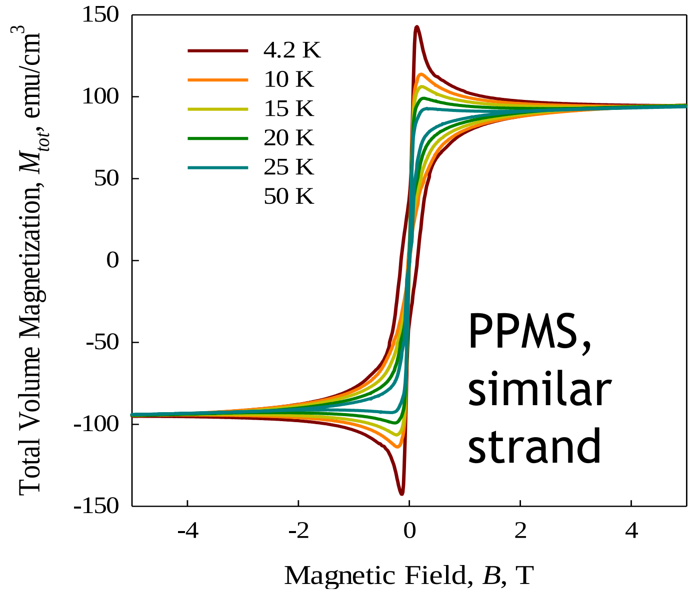
3 T Magnet
Dipole Magnet

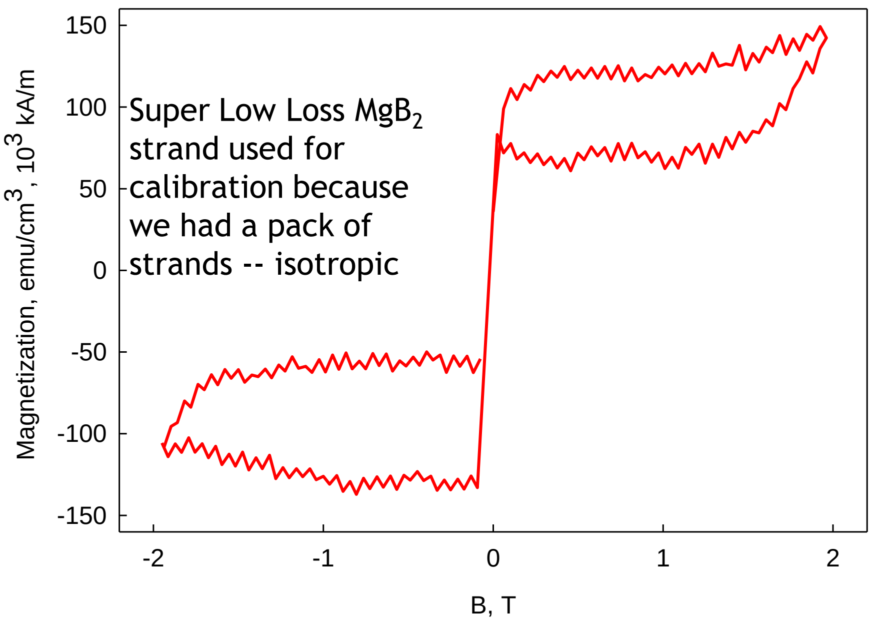
Max Field = 3.1 T
Max I = 90 A
L = 1 H
Max Ramp Rate = 70 mT/s

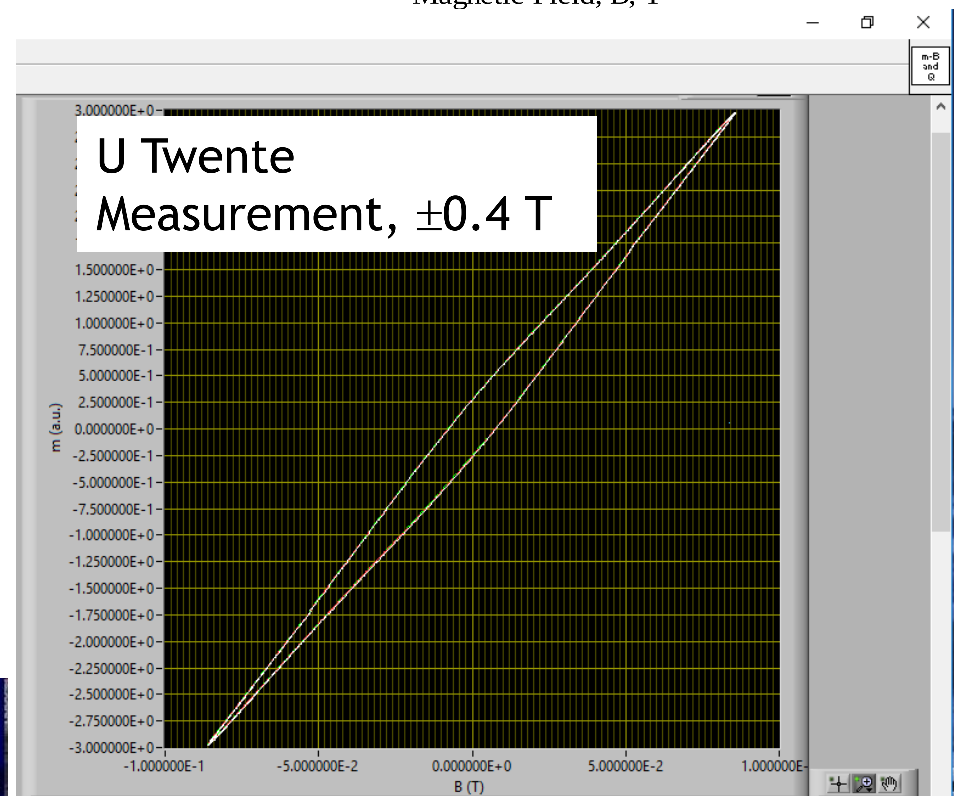


Initial calibration runs



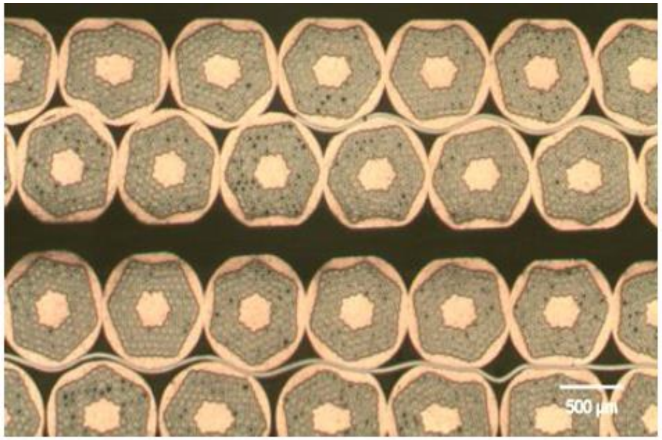






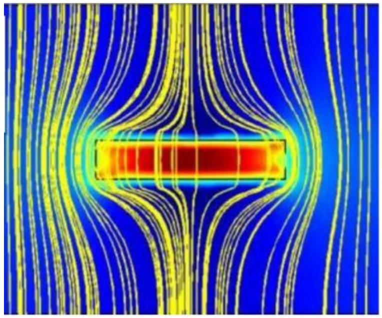
Next Measurements

- Nb_3Sn Cable stacks
- Roebel Cables
- CORC Cables
- Twist Stack
- Samples from LBNL



Magnetization Calculations for YBCO Tape, CORC, TWST, and Roebel

Assume w = 4 mm, t = 0.1 mm
J_e = 2000A/.4 mm^2=5000 A/mm^2 At injection



For tapes with $B >> B_p$

Based on tape width and Je

$\Delta M = aJ_c$ M = (5*10^9)*(2e-3) = 10e+6A/m = 10000 kA/m = 12.5 T

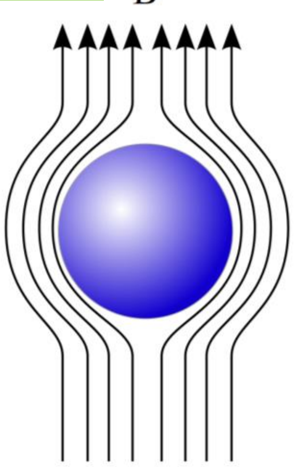
Penetration field

Magnetization in full penetration factor of 2, tape/cable

$$H_p = \frac{J_c t}{\pi}\left[Ln\left(\frac{w}{t}+1\right)\right] = \frac{5}{2\pi}H_d\left[Ln\left(\frac{w}{t}+1\right)\right]$$

$B_p = 4J_c t\ 10^{-7}(\mathrm{Ln}(1000)) = 6*4\ x10^{-1}*5x10^{9-7} = 120$ mT

But M controlled by Bp, and Bp different x 10



For Long pitch CORC

$\Delta M = \left(\frac{2}{\pi}\right)aJ_c$ M = $(2/\pi)M_{tape}$= 6369 kA/m = 7.96 T

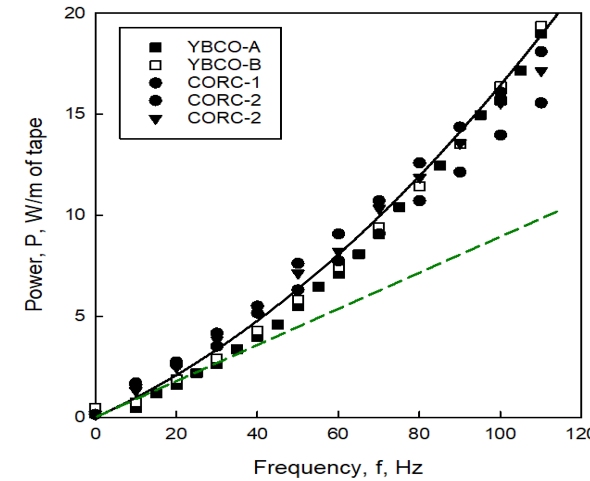
For the penetration field we must use a dilute SC model

$\boldsymbol{B_p = \mu_0 J_{c,dilute} t_{corc\ wall}}$ B_p = (1.2 x 10^{-6})*5x10^9*0.3x10^{-3}= 1.8 T

Compare to experiment: CORC

Data taken by our group at Twente

Direct compare measurements at AFRL show CORC loss is 2/Pi*tape loss

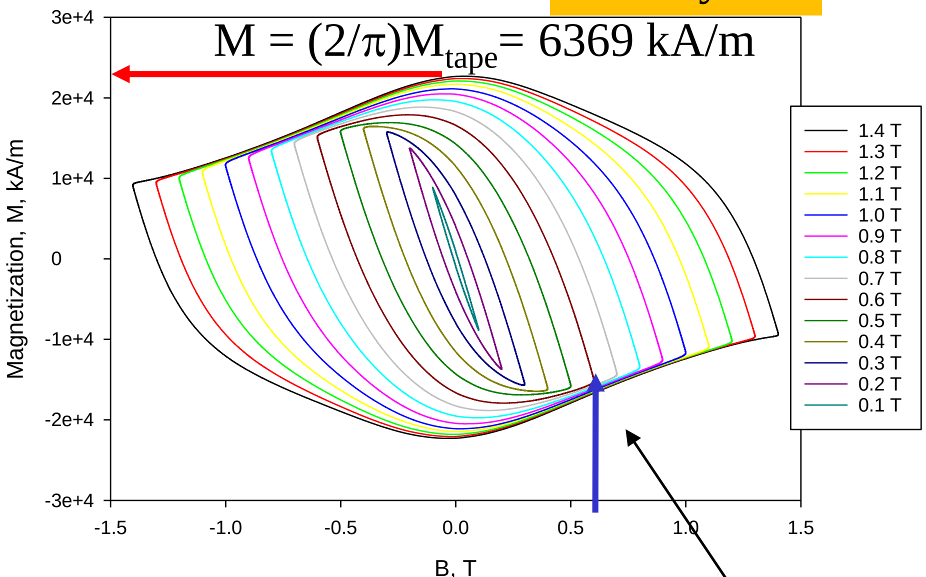


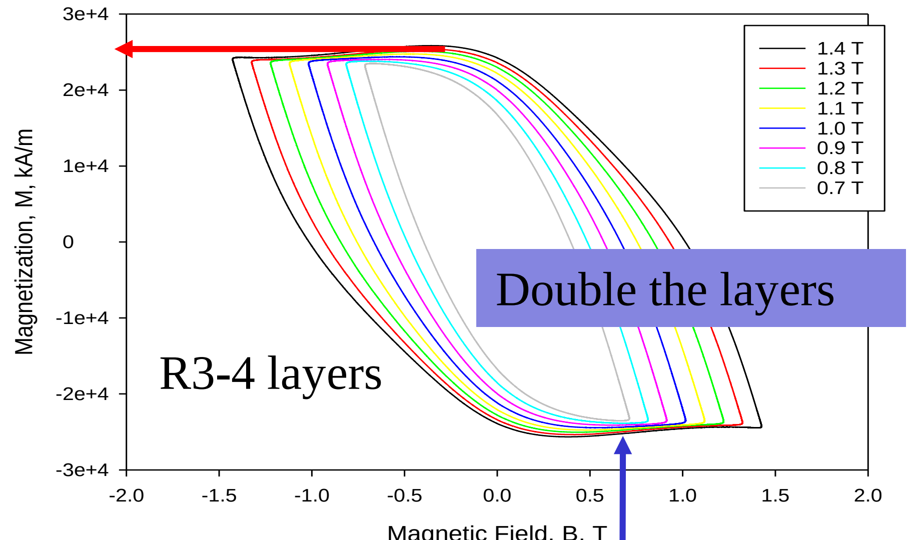
Normalized to tape volume, 4 K result

R1-2 layers

Few layers

$M = (2/\pi)M_{tape} = 6369$ kA/m





Double the layers

R3-4 layers

	Film norm	Film norm	tape norm
	A/m	kA/m	kA/m
del M=	500000000	500000	10000

$B_p = (1.2 \times 10^{-6})*2.5\times10^{9}*0.2\times10^{-3} = 0.6$ T

Estimations for LBNL CORC samples

- CORC A: 16-tape wire, wire OD 3.09 mm (including the heat shrink tubing), I_c = 4 kA at 4.2 K, self-field
- CORC B: 29-tape wire, wire OD 3.63 mm (including the heat shrink tubing), I_c = 11 kA at 4.2 K, self-field

<u>For Tape A:</u> I_c = 262 A per tape (0.04 mm thick, 2 mm wide, gives J_e = 262/.08 mm^2 = 3275 A/mm^2 = 3.27 x 10^9 A/m^2)

<u>For Tape B:</u> I_c = 379 A per tape (0.04 mm thick, 2 mm wide, gives J_e = 379/.08 mm^2= 4741 A/mm^2 = 4.74 x 10^9 A/m^2)

<u>Magnetization Tape A:</u> $M=J_c a/2$=3.27 x 10^9 A/m^2 * 10^{-3} m = 3270 kA/m

<u>Magnetization Tape B:</u> $M=J_c a/2$=4.74 x 10^9 A/m^2 * 10^{-3} m = 4740 kA/m

<u>Magnetization CORC A:</u> $M=(2/\pi)M_{tape}$*0.38*0.8= 633 kA/m

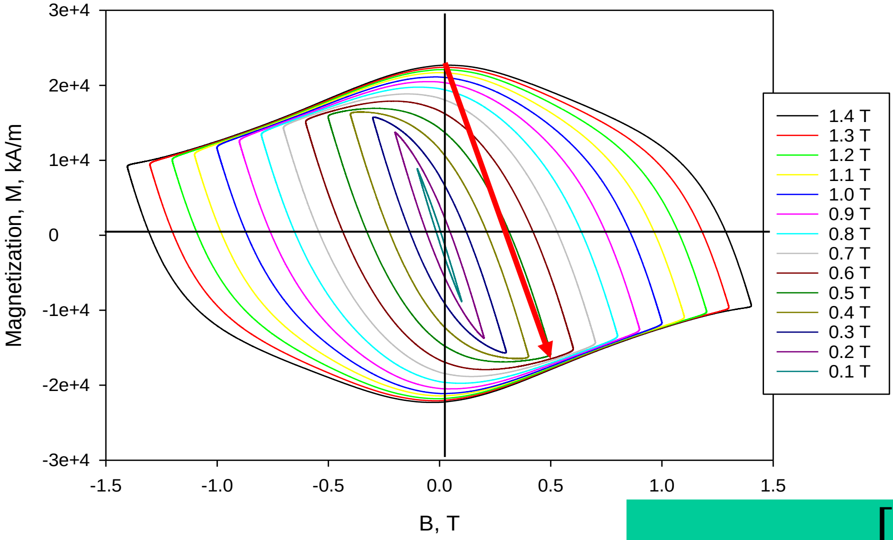
<u>Magnetization CORC B:</u> $M=(2/\pi)M_{tape}$*0.45*0.8= 1086 kA/m

Above Bp, but see below!

<u>Penetration field CORC A:</u> ***$B_p = \mu_0 J_{c,d} t_{wall}$=1.25x10^{-6}x3.27x10^9 A/m^{2}x3.79 x 10^{-4}m=1.55 T (about 0.155 T at 77 K)***

<u>Penetration field CORC B:</u> ***$B_p = \mu_0 J_{c,d} t_{wall}$=1.25x10^{-6}x4.74x10^9 A/m^{2}x4.75 x 10^{-4}m=2.81 T (about 0.281 T at 77 K)***

CORC Magnetization Near Injection

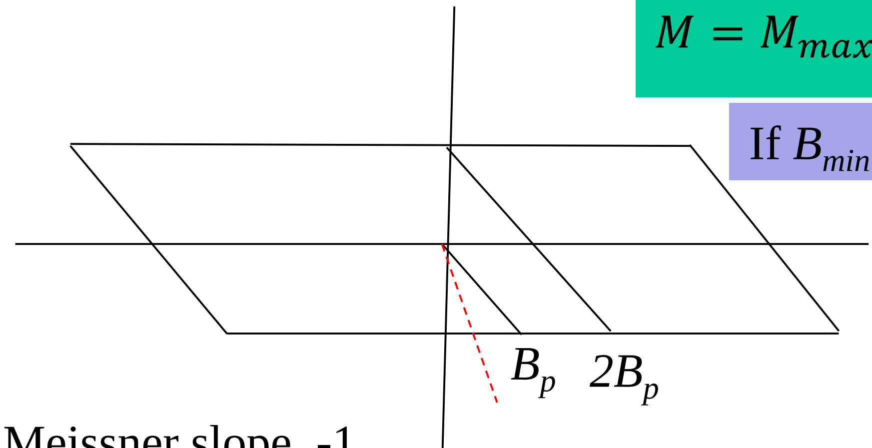


Very generally, the CORC can be <u>treated as a simple tape of effective width</u>

w_{eff} = (2/π)(fill factor)(1-$w/3L_p$)

If $B_{min} = 0$

$$M = M_{max}\left[1-\left(\frac{B}{B_p}\right)\right] = \frac{2}{\pi}\frac{J_c a}{2}FF\left[1-\frac{w}{3L_{p,eff}}\right]\left[1-\left(\frac{B}{B_p}\right)\right]$$



If $B_{min} \neq 0$

$$M = M_{max}\left[1-\left(\frac{B-B_{min}}{B_p}\right)\right]$$

$$= \frac{2}{\pi}\frac{J_c a}{2}FF\left[1-\frac{w}{3L_{p,eff}}\right]\left[1-\left(\frac{B-B_{min}}{B_p}\right)\right]$$

Meissner slope, -1

$$Bean\ Slope = \frac{M_{max}}{H_p} = -\frac{J_c\left({}^{a}/_{2}\right)}{J_c a} = -\frac{1}{2}$$

In full penetration

$$M = M_{max} = \frac{2}{\pi}\frac{J_c a}{2}FF\left[1-\frac{w}{3L_{p,eff}}\right]$$

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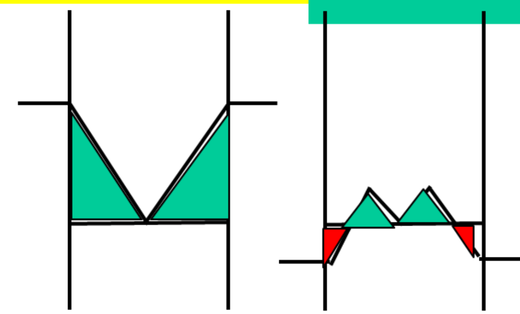
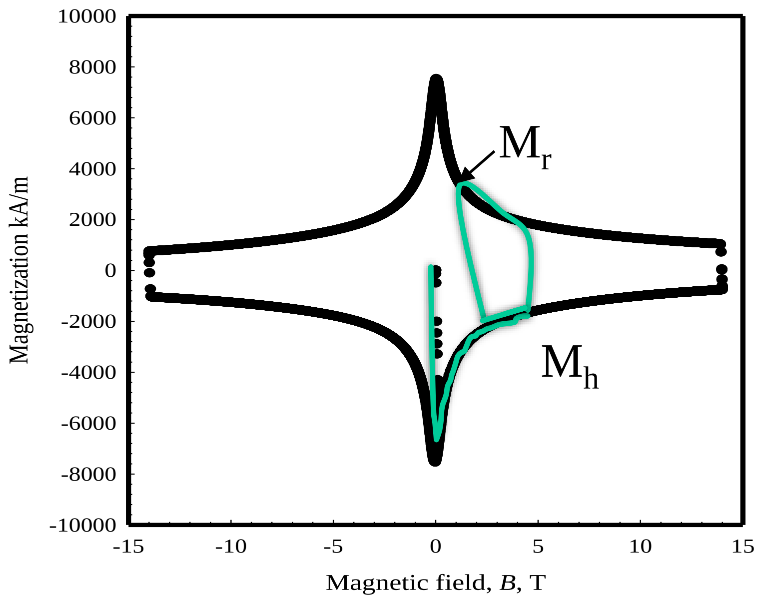
Reduction of M and M drift at injection

- Here we show that we can reduce both the Remanant magnetization and creep at injection using a modified field cycle
- First from zero go to high field (5 T), then a lower rest field (0-1 T), and then to 1 T for “injection”

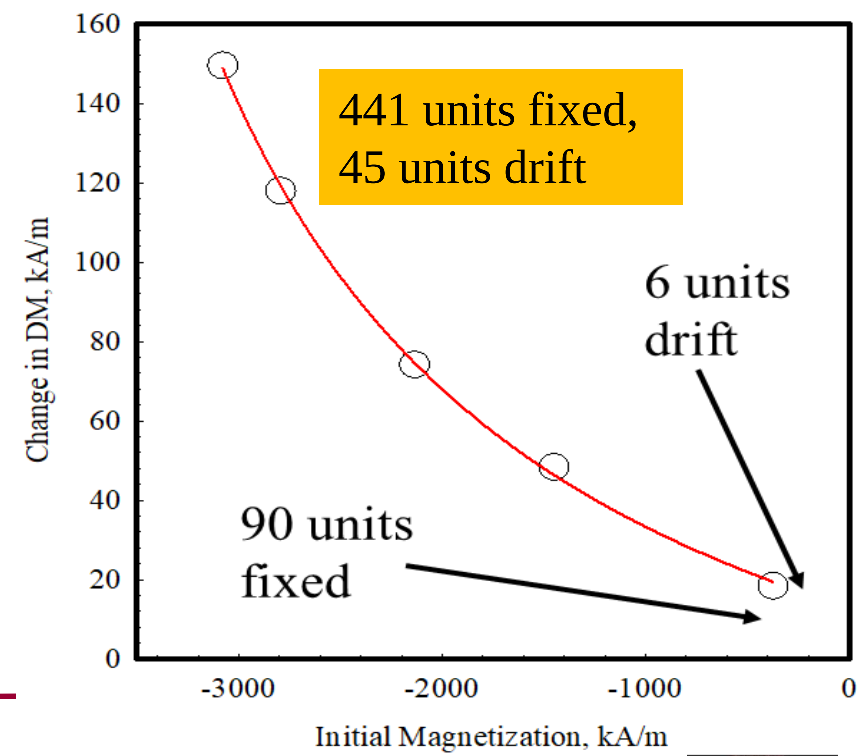
0 T →5T (“collision”) → 0 T → 1 T (inj)	0 T →5T (“collision”) → Mr (0-1 T) → 1 T (inj)



$M_{inj} \propto$ green area $M_{inj}(t) \propto (A_G)*(1-\mathrm{Ln}(t))$	$M_{inj} \propto$ green area-red area $M_{inj}(t) \propto (A_G-A_R)*(1-\mathrm{Ln}(t))$



With a resting field (B_{min}) of 0.96 T, we can highly suppress both remanent magnetization, and its drift



Summary

- *M-H* of CORC and twist stack in full penetration calculated by Analytic and FEM methods
- For long L_p, $M_{corc} = M_{twst} = (2/\pi)M_{tape}$

  This CF ≈0.8
- *In general*

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2w}{3L_p}\right)$$

$$\Delta \mathrm{M} = \Delta M_0 \frac{L_p}{\pi w} \cos\left[\frac{\pi L_p}{4}\left(1 - \frac{w}{L_p}\right)\right]$$

- Hall probe short cable system online
- 3 T dipole system for 30 cm cable magnetization/loss online
- Drift suppression for YBCO with cycle modifications
- Further Measurements of the most recent cables, expanded up to +- 3 T at 4 K
- Expressions for CORC Magnetization at arbitrary fields near injection have been developed as part of LBNL-OSU collaboration (X. Wang) YBCO data for error estimations

$$M = \frac{2}{\pi}\frac{J_c a}{2} FF\left[1 - \frac{w}{3L_{p,eff}}\right]\left[1 - \left(\frac{B - B_{min}}{B_p}\right)\right]$$